PASSIVE, HIGH-TEMPERATURE AMPLIFIER FOR AMPLIFYING SPARK SIGNALS DETECTED IN IGNITER IN GAS TURBINE ENGINE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This Application is related to subject matter in the following patent applications, which are of common inventorship and filed concurrently herewith:

SENSOR FOR DETECTION OF SPARK IN IGNITER IN GAS TURBINE ENGINE, SN __/___,___;

METHOD OF INFORMING PILOT OF AIRCRAFT OF SPARK DETECTED IN GAS TURBINE ENGINE, SN __/___,___;

INTEGRAL SPARK DETECTOR IN FITTING WHICH SUPPORTS IGNITER IN GAS TURBINE ENGINE, SN __/___,___;

DETECTING SPARK IN IGNITER OF GAS TURBINE ENGINE BY DETECTING SIGNALS IN GROUNDED RF SHIELDING, SN __/___,___; and

SPARK IGNITER FOR GAS TURBINE ENGINE, SN __/___,___.

FIELD OF THE INVENTION

[0002] The invention relates to gas turbine engines, and igniters therein.

BACKGROUND OF THE INVENTION

[0003] This Background will explain why the lack of absolute certainty in lifetimes of igniters used in gas turbine aircraft engines can impose significant costs on the owners of the aircraft utilizing the engines.

[0004] Figure 1 is a highly schematic illustration of a gas turbine engine 3, containing a combustor 6. Fuel 9 is sprayed into the combustor. An igniter 12, which functions in a roughly analogous manner to a spark plug in an automobile, produces a spark, or plasma discharge (not shown), which initially ignites the jet fuel.

[0005] After initial ignition, the igniter 12 can be repeatedly sparked thereafter, primarily as a safety measure. That is, in a modern engine, under normal circumstances, it is extremely unlikely for a flame-out to occur in the combustor 6. However, unexpected situations, such as an abrupt cross-wind, can affect the environment within the combustor, and resulting loss of flame.

[0006] In addition, certain flight conditions make the unlikely event of a flame-out slightly more probable. Thus, for example, the igniter 12 may be activated when the aircraft enters a rain squall, or other situation which may disturb steady-state conditions in the combustor 6.

[0007] The igniters 12, like all mechanical components, have useful lives which eventually expire, at which time the igniters must be replaced. However, this expiration-and-replacement can create a situation in aircraft which is expensive.

[0008] A primary reason is that the approach of an igniter to the end of its lifetime is not marked by readily detectable events. That is, at some point, the igniter completely ceases to generate a plasma, or spark. However, prior to that point, the igniter may sporadically generate sparks.

[0009] As explained above, the sparking is not, in general, required to maintain the combustor flame. Consequently, the sporadic sparking would only be noticed if an actual flame-out occurred, and if the sporadic sparking were ineffective to induce a re-light. Since such a combination of events is seen as unlikely, the sporadic sparking is not readily noticed. The impending expiration of the useful life of the igniter is similarly not noticed.

[0010] Another reason is that, while all igniters may be constructed as identically as possible, nevertheless, those igniters do not all possess the same lifetimes. Nor do all igniters experience identical events during their lifetimes. Thus, it is not known exactly when a given igniter will expire.

[0011] Thus, the point in time when an igniter must be replaced is not known with certainty. One approach to solving this problem is to perform preventative maintenance, by replacing the igniters when they are still functioning. While the cost of a new igniter and the manpower required to install it is not great, the early replacement does impose another cost, which can be significant.

[0012] The aircraft in which the igniter is being replaced represents a revenue source measured in thousands of dollars per hour. If the aircraft is rendered non-functional for, say, two hours during replacement of an igniter, the revenue lost during that time is substantial.

[0013] Therefore, the uncertain lifetimes of igniters in

gas turbine aircraft engines can impose significant losses in revenue.

SUMMARY OF THE INVENTION

[0014] Normal operation of an igniter in a gas turbine engine causes erosion of an insulator inside the igniter. In one form of the invention, an auxiliary ground electrode is embedded within that insulator, and the erosion eventually exposes the auxiliary electrode. The igniter is designed so that the exposure occurs at the time when the igniter should be replaced.

[0015] The exposed auxiliary ground electrode can be detected by the fact that, when a spark occurs, a small current travels through the auxiliary ground electrode. When that current is detected, its presence indicates the exposure. Alternately, the exposed auxiliary ground electrode can be visually detected by a human observer, perhaps by using a borescope.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Figure 1 is a simplified schematic of a gas turbine engine.

[0017] Figure 2 illustrates an igniter 12, shown in Figure 1.

[0018] Figures 3 and 4 are enlarged views of end E in Figure 2.

[0019] Figures 5 and 6 illustrate changes in geometry of end E which the Inventors have observed.

[0020] Figure 7 illustrates one form of the invention.

[0021] Figures 8 and 9 are views resembling insert 84 in Figure 7.

[0022] Figure 10 is a perspective view of part of Figure 7.

[0023] Figure 11 is a perspective, cut-away view of one form of the invention.

[0024] Figure 12 is a cross-sectional view of the apparatus of Figure 11.

[0025] Figure 13 is a perspective view of the apparatus of Figure 11.

[0026] Figure 14 illustrates one form of the invention.

[0027] Figure 15 illustrates a sequence of events occurring in one form of the invention.

[0028] Figure 16 illustrates two distances D9 and D10, over which two electric fields are generated.

[0029] Figure 17 illustrates one mode of constructing auxiliary electrode 72 in Figure 15.

[0030] Figure 18 illustrates an aircraft which utilizes one form of the invention.

[0031] Figure 19 illustrates igniter 308, bearing an annular coil 310.

[0032] Figure 19A illustrates one form of the invention, wherein a bracket 311 supports the igniter, and also contains a coil 310.

[0033] Figure 20 illustrates an igniter-cable assembly

about which is positioned a high-permeability ring 326, about which is wrapped a coil 320.

[0034] Figure 21 is a schematic of one view of an igniter system.

[0035] Figure 22 is a schematic developed by the Inventors of a possible mode of operation of the apparatus of Figure 21.

[0036] Figure 23 illustrates a prior-art RLC circuit.

[0037] Figure 24 illustrates an RLC circuit excited by a sinusoidal waveform.

[0038] Figures 25 - 28 are plots of simulated output of the circuit of Figure 24.

[0039] Figure 29 illustrates an RLC circuit pulsed by a pulse train.

[0040] Figures 30 - 34 are plots of simulated output of the circuit of Figure 29.

[0041] Figure 35 illustrates timing parameters.

[0042] Figure 36 illustrates two forms of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0043] Figure 2 illustrates an igniter 12 used in the prior art. An electrical connector (not shown) is threaded onto threads 21, and contains an electrical contact (not shown) which mates with the end 24 of electrode 27. Insulator 30 isolates electrode 27 from the shell 33 of the igniter 12.

[0044] End E of the igniter 12 is shown in Figures 3 and 4. A very simplified explanation of the physics involved in plasma

generation will be given.

[0045] In operation, a high voltage is applied to the electrode 27, thereby creating a voltage difference, or potential difference, V between points P1 and P2 in Figure 3. The electric field in that region equals the potential difference V divided by the distance D between the points P1 and P2. For example, if the voltage is 20,000 volts and the distance D is 10 millimeters, or 0.01 meter, then the electric field equals 20,000/0.01, or 2 million volts per meter.

[0046] The electric field is designed to exceed the dielectric breakdown strength of the material, or medium, lying between points P1 and P2. That material is a mixture of air plus fuel. However, the field does not exceed the breakdown strength of insulator 30, and that strength exceeds that of the air-fuel mixture.

[0047] When breakdown occurs, the electric field strips electrons away from the atoms in the medium, producing positively charged ions and free electrons. The electric field drives the free electrons in a direction parallel with the electric field. However, during that movement, those temporarily free electrons will collide with other ions. Also, thermal motion of the ions and electrons will also bring them together in collisions.

[0048] In the collisions, the electrons will be captured by the ions, and will drop to a lower energy state, releasing heat and light, in the form of an electric arc which is called a plasma, which is indicated as lightning bolt 40 in Figure 4. This process

continues as long as the electric field is present.

[0049] The Inventors have observed one result of the operation just described. As indicated in Figure 5, the insulator 30 becomes eroded from the phantom shape 50 to the curved shape 53. In addition, the electrode 27 becomes eroded from the phantom shape 56 to the solid shape 59. Corners 33A also become eroded.

[0050] The Inventors believe that one or more of the following agencies are responsible for the erosion. One agency is the corrosive nature of the plasma: free electrons are very reactive, and seek to bind to any available atoms or ions which are nearby. Also, the generation of free electrons from oxygen, which is present in the air, creates ionized oxygen, which is also highly reactive.

[0051] A third agency is that the plasma creates a high-temperature environment. A high temperature, by definition, represents agitated atoms and molecules with high velocities. High-velocity atoms and molecules react more readily with stationary objects when they collide with the objects.

[0052] Possibly a fourth agency is the fact that the plasma generates high-frequency photons, in the ultra-violet, UV, and perhaps into the X-ray regions of the spectrum. It is well known that UV and X-radiation can damage numerous types of material.

[0053] Irrespective of the precise causes of the erosion, the erosion illustrated in Figure 5 eventually causes the igniter 12 to eventually stop functioning. A primary reason is illustrated in Figure 6. Previously, prior to the erosion, voltage was applied

between points P1 and P2 in Figure 6. However, after the erosion, point P2 has effectively moved to point P3. Distance D has now become longer distance D2. The electric field, which causes the ionization and thus the plasma, is now weaker.

[0054] Continuing the example given above, if distance D2 is 20 millimeters, then the electric field becomes 20,000/0.020, or one million volts per meter, half its original value. Eventually, distance D2 becomes so great that the electric field does not reliably exceed the dielectric breakdown strength of the air-fuel mixture, and ionization ceases to occur.

[0055] Figure 7 illustrates one form of the invention. An auxiliary electrode 72 is embedded in the insulator 75. The tip 78 is covered by the insulator-material in region 81, as indicated by the insert 84. Auxiliary electrode 72 may be connected to the shell 33, as at region 90.

[0056] Initially, current enters electrode 27 as indicated by arrow 84, jumps to the shell 33 through the plasma 85, and exits the shell 33 into the engine, through multiple paths, such as through its mounting threads, as indicated by arrow 86.

[0057] As erosion occurs, the insulator 75 departs from its initial shape indicated by phantom lines 92 in Figure 8. Tip 78 of the auxiliary electrode 72 now becomes exposed. Now, when a high voltage is applied to the igniter, two paths exist for a plasma to follow. One is the usual path P5 in Figure 9. The other path is indicated as P6 of Figure 9, and runs from the central electrode 27 to the now-exposed auxiliary electrode 72.

[0058] Restated, two current-return-paths are available to the central electrode 72. Path P5 runs to the shell 33, in the usual manner. Path P6 runs to the now-exposed auxiliary electrode 72. Eventually, further erosion will lengthen path P5, and cause plasma formation along that path to terminate. That is, path P5 in Figure 9 initially can be represented by distance D in Figure 6. After sufficient erosion, path P5 in Figure 9 will be represented by distance D2 in Figure 6, and, as explained above, no plasma will be generated along path P5 when distance D2 becomes sufficiently large.

[0059] However, auxiliary plasma path P6 is still available in Figure 9 at this time. A plasma can still be generated, and the lifetime of the igniter has been increased.

[0060] The preceding discussion presented the auxiliary electrode 72 in Figure 7 in the form of a rod. Figure 10 illustrates such a rod in perspective view, surrounded by insulator 75.

[0061] In an alternate embodiment, a cylinder is used. Figure 11 is a cut-away view of one embodiment. Central electrode 27 is surrounded by an insulator 100, which itself is surrounded by a conductive tube or cylinder 103, which is then surrounded by another layer of insulator 105. Figure 12 illustrates the system in cross-sectional view, with similar numbering.

[0062] Figure 13 illustrates the insulator 100 in its initial configuration, after manufacture or just after installation. A tip 110 of central electrode 27 is exposed, and

surrounded by the conical surface 113 of the insulator 100. Cylindrical auxiliary electrode 103 is embedded within the insulator 100, and no tip or edge is exposed, as indicated by distance D8 in Figure 12.

[0063] The preceding discussion stated that the auxiliary electrode 72 may be connected at region 90 in Figure 7. In another embodiment, the auxiliary electrode 72 of Figure 14 is also connected to ground, but through a detector 150. Detector 150 looks for a current in auxiliary electrode 72. Current detectors are well known.

[0064] If no current is detected, it is inferred that the auxiliary electrode 72 is still embedded within insulator 75, as in Figure 7, and is electrically isolated from central electrode 27.

[0065] In contrast, if a current is detected, it is inferred that the auxiliary electrode has become exposed through erosion, as in Figure 9. The detected current is attributed to a plasma following path P6. When the current is detected, detector 150 issues a signal, sets a flag, or otherwise indicates the inference that erosion has exposed auxiliary electrode. A human technician at that time, or a prescribed time afterward, replaces the igniter.

[0066] An alternate mode of detection is to remove the igniter and visually examine the end corresponding to end E in Figure 2. If a smooth surface of the insulator 100 is seen, as in Figure 13, then it is concluded that the igniter is still

functional. However, if the auxiliary electrode 72 is seen, as in Figure 8, then it is concluded that replacement may be required.

[0067] In another embodiment, the auxiliary electrode is designed to become exposed, and then to erode rapidly. Figure 15, viewed left-to-right, illustrates first a newly installed igniter 160. After a period of usage, igniter 165 exposes its auxiliary electrode 72. Now a plasma P6 extends to the auxiliary electrode 72.

[0068] However, as stated above, the auxiliary electrode 72 is designed to erode rapidly. For example, as insert 170 indicates, the auxiliary electrode 72 is fabricated with a pointed end. Plasma 6 causes the pointed end to become rapidly eroded, as indicated by the small particles in frame 170. This operation causes a specific sequence of two events.

[0069] One is that, when the auxiliary electrode becomes first exposed, a current passes through the it. The current is detected, as by detector 150 in Figure 14. Next, after the auxiliary electrode fractures or erodes, no current passes through it.

[0070] One reason for this sequence is illustrated in Figure 16. Initially, the voltage V spans distance D9, creating an electric field equal to V/D9. After fracture or erosion, the same voltage V spans distance D10. The electric field equals V/D10, a smaller value. The latter electric field is insufficient to create a plasma, while the former is.

[0071] In one embodiment, the occurrence of the two events

just described occurs prior to the termination of the lifetime of the igniter. Thus, that termination is signalled by the occurrence of a current through the auxiliary electrode 72, followed by a termination of that current. The onset of the current indicates the approach of the termination of the lifetime, but with time remaining to operate the engine. The subsequent termination of the current indicates that less time remains, and that replacement of the igniter becomes more important.

[0072] Figure 17 illustrates one embodiment of the auxiliary electrode 72. A neck, or groove, 190 is provided, which facilitates the breakage schematically illustrated in the insert 170 in Figure 15. The groove 190 is a region of mechanical weakness intentionally built into the auxiliary electrode 72. Prior to the erosion indicated in Figure 8, that weakness is not important, because mechanical support to the electrode is supplied by the insulator 75.

[0073] The discussion above stated that a high voltage is applied to electrode 27. It is possible that a low voltage applied to the electrode 27 can accomplish the same function of generating a plasma.

[0074] Figure 18 illustrates another embodiment. An aircraft 300 is powered by gas turbine engines (not shown), which are located within nacelles 305. Each engine contains one, or more, igniters, as discussed above. The igniters may contain an auxiliary electrode, as described above, or may be of the prior-art type.

[0075] Figure 19 illustrates an igniter 308. The invention adds a sensor, such as sensing coil 310. This coil 310 is coaxial with the igniter, as indicated. This particular coaxial arrangement was used in an experiment, to ascertain whether a coil could detect a signal when the igniter 308 produced a spark.

[0076] The coaxial arrangement is not necessarily required. In one form of the invention, coil 320 can be arranged as shown in the two rightmost images in Figure 20. The magnetic field lines B produced by current I in the power cable 315 are concentric with the current which produces the field lines B. Since that current flows though the entire cable 315, and through the igniter 308, the field lines B extend along both the cable 315 and the igniter 308.

[0077] According to Faraday's Law, optimal coupling is attained when the coil 320 is perpendicular to the field lines B, as shown in the central image.

[0078] In another form of the invention, a high-permeability ring 326, constructed perhaps of transformer iron, is placed about the igniter, or cable 315, and the coil 320 is wrapped about the ring 326. The ring 326 captures the magnetic field lines B, as it were, and delivers them to the coil 320. Under this arrangement, field lines B passing through the ring 326 also pass through the coil 320.

[0079] One definition of the term high permeability is that the relative permeability of a high permeability material exceeds 1,000. As a point of reference, the relative permeability of many

steels is in the range of 4,000. Materials exist having relative permeabilities approaching one million.

[0080] In yet another form of the invention, a prior-art clamp-on current detector (not shown) is used.

[0081] The Inventors have found that the coil 310 in Figure 19, even though lacking the perpendicular characteristic shown in Figure 20, produced a detectable signal in response to current pulses within the igniter 308. The Inventors offer the following observations concerning this signal, and its detection.

[0082] Figure 21 is an electrical schematic of the igniter circuit. Block 330 represents the exciter, which is contained within a conductive housing (not shown). The exciter 330 produces a high-voltage pulse train, to generate spark in the igniter 340.

[0083] Power cable 335 delivers the high-voltage current pulses to the igniter 340. One type of high-voltage pulses are in the range of 20,000 volts. One type of frequency of the pulses lies in the range of 10 Hz, that is, ten pulses per second. One type of pulse has a duration of 10 milliseconds. In this example, the duty cycle is thus ten percent (0.10/0.100).

[0084] Plot 331 illustrates the pulses just described. Duration D would be 10 milliseconds in this example. Period T would be 100 milliseconds in this example, corresponding to a frequency of 1/T, or 10 pulses per second.

[0085] In Figure 21, a shield 345 surrounds the power cable 335. The shield 345 can take the form of solid conduit, a woven conductive sleeve, a combination of the two, or other types of

shielding. This shield 345 is connected to the casing 350 of the igniter 340, and the casing 350 is connected to the frame, or housing, 352 of the engine, which is considered to be a DC ground.

[0086] The shield 345 provides electromagnetic interference suppression and also prevents personnel from contacting the high-voltage cable 335. Even though the cable 335 is itself surrounded by a thick insulating cover, the shield 345 provides a redundant safety measure.

[0087] Under the arrangement illustrated, the housing (not shown) of the exciter 330, the shield 345, and the casing 350 of the igniter 340 are all connected to the frame 352 of the engine, and are considered to be held at DC ground.

[0088] One type of classical analysis of the apparatus shown in Figure 21 states that the following mechanism can explain the sparking operation. During each high-voltage pulse, of duration D in plot 331, the current provided by the high-voltage cable 335 reaches the spark gap 355, jumps the gap 355, and returns via the frame of the engine, to the exciter 330, along path 360. Under this mechanism, arguments can be mustered indicating that the coil 310 of the type shown in Figure 19 would be ineffective to detect the current pulses.

[0089] A basic argument is that, in theory, coil 310 should detect no current, because no magnetic field lines B, in theory, penetrate the cross-sectional area of the coil 310. Faraday's Law states that such penetration is required.

[0090] In considering additional arguments, two cases

should be distinguished: the DC case and the AC case. In the DC case, if a DC current is carried by the high-voltage cable 335 in Figure 21, then static magnetic field lines B of the type shown in Figure 20 would be present. If the coil is placed around the igniter as shown in Figure 19, and if the casing 350 of the igniter is constructed of a high-permeability material, such as a type of steel, the casing will trap some, or all, of the B-field, and possibly inhibit detection of the static B-field. It could be said that the shielding, including the casing 350 of the igniter and the shield 345, act as a Faraday cage which contains the static DC magnetic field. Thus, an argument may exist stating that coil 310 in Figure 19 would not detect the current pulses.

[0091] This argument may also apply to slowly varying currents. That is, it is possible that the Faraday cage also blocks slowly changing magnetic fields.

[0092] In the AC case, electromagnetic radiation may emanate from the cable 335 and igniter 350 in Figure 21, particularly because the current pulses contain high-frequency components. High-frequency components, in general, radiate more readily, at least from short antennas of length equal to fractions of a wavelength. The conductivity, as opposed to permeability, of the shield 345 and casing 350 can block radiation produced by the current pulses. In one mechanism, the blockage occurs through reflection: the radiated electromagnetic field induces currents in the shield 345 and casing 350, which radiate their own electromagnetic fields inwardly, toward the cable 335. The

radiated fields, in effect, reflect the incoming radiation back to the cable 335.

[0093] Also, as stated above, the shield 345 and igniter casing 350 are connected to ground. In theory, those grounded elements shunt all AC signals to ground, and thus prevent them from radiating electromagnetic energy.

[0094] Thus, at least the preceding arguments exist which indicate that the coil of Figure 19 would not be effective to detect current pulses in the cable 335 of Figure 21.

[0095] The Inventors have observed, or postulated, that all the return current may not follow path 360 in Figure 21. Return current refers to that returning to the exciter 330 after having jumped the spark gap 355. The Inventors surmised that some return current may travel along the shielding system, including the shield 345 and the casing 350 in Figure 21. Figure 22 is one representation of this surmise.

[0096] Resistor R1 indicates the small resistance of the ground path through the engine frame, from the spark gap 355 to the exciter, and corresponds roughly to path 360 in Figure 21. Resistor R2 indicates the small resistance of the path from the spark gap 355 to the exciter, but through the shield system. The shield system includes the casing 350 of the igniter and the shield 345. Both R1 and R2 originate at, or near, the spark gap 355, but represent different routes to the exciter 330.

[0097] Under this surmise, it is possible that the return current passing through R2 is detectable, despite the arguments

given above.

[0098] In this context, the Inventors point out that, in general, detecting a return current through the other resistor R1 is considered impractical. Resistor R1 represents, among other things, the engine itself. A simple, accurate, and reliable approach to detecting return current in the engine is not seen as practical, at least for the reason that the number of paths available to the return current is so large, in spanning the entire engine, or a large part of it.

[0099] However, the path represented by resistor R2 is a localized, discrete entity, from a current-detection standpoint, and is not contained within a shield. Thus, if a return current pulse is travelling in R2, then the magnetic field, or electromagnetic radiation, produced by the pulse may be detectable, by detecting the current in R2, that is, the current in the shield system.

[0100] An experiment was undertaken, using coil 310 in Figure 19, and it was found that coil 310 produced a detectable signal, when the exciter produced a spark pulse.

[0101] It should be observed that the coil 310 may be detecting one, or more, of the following currents. Coil 310 may be detecting the current pulse in the cable 335 in Figure 21, contrary to the arguments given above: the shielding system may not be completely effective. Alternately, coil 310 in Figure 19 may be detecting return current pulses in the casing 350 of the igniter, as postulated above. Or coil 310 may be detecting some

type of sum or difference of the two currents just identified.

[0102] The signal detected in coil 310 was small, so that amplification may be desired. However, the operational environment of the coil 310 provides a challenge in this respect.

[0103] During operation of the aircraft 300 of Figure 18, coil 310 in Figure 19 will be located in an environment having a temperature exceeding 400 F. That is, the casing 350 of the igniter 308 in Figure 19, to which the coil 310 is attached or adjacent, exhibits a temperature of at least 400 F during normal operation.

[0104] Such a high temperature would cause problems if a solid-state amplifier is to be used to amplify signals produced by coil 310. Nevertheless, with sufficient precautions, an electronic, transistorized amplifier could be used to detect the signals produced by the coil 310.

[0105] In one form of the invention, no solid-state amplifier is used, at least not in the vicinity of the 400 degree environment. Instead, a passive amplifier was developed, using only resistive, capacitive, and inductive elements, with no active elements such as transistors or vacuum tubes. One definition of active element is that an active element can amplify power of an input signal: output power can exceed input power. A passive element does not possess that property of power amplification.

[0106] It is known that a series RLC circuit, such as that in Figure 23, can be designed to produce an amplified voltage across the capacitor C under certain conditions. This

amplification is discussed in Chapter 13, entitled "Frequency Response," in the text entitled "Engineering Circuit Analysis," by William Hayt and Jack Kemmerly (ISBN 0-07-027410-X, McGraw-Hill, 1993). This text is hereby incorporated by reference.

[0107] The conditions for amplification include the following. One, the signal source, Vin, be sinusoidal, and of constant frequency, which is a situation often called sinusoidal steady-state. Two, the values of the capacitor C and inductor L are chosen so that the input impedance seen at points P1 and P2 is purely real, with no reactive components. This condition is called resonance, and the value of the resonance frequency, omega-sub-zero, is indicated in Figure 23.

[0108] Under these conditions, the voltage across the capacitor, Vc, will equal ABS(Q) x Vin, as indicated in Figure 23, wherein ABS refers to the absolute value, or magnitude, of the Quality factor Q of the circuit. Q is defined as indicated in Figure 23. Thus, for example, for a Q of 10, a tenfold amplification is attained.

[0109] Thus, the prior art indicates that a series RLC circuit can provides voltage amplification to a sine wave input. The text identified above indicates that the dual of a series RLC circuit, namely, a parallel RLC circuit, provides current amplification, as opposed to voltage amplification.

[0110] A computer simulation will illustrate the voltage amplification.

[0111] Figure 24 illustrates a circuit which was simulated

using one of the commercially available SPICE programs. The transformer 372 is present, in order to make this circuit consistent with the circuit models of the invention, later discussed. Values of the resistor R, capacitor C, and inductor L are indicated. These values remained constant in all simulations.

[0112] Figures 25 - 28 illustrate results of four simulations done on the circuit of Figure 24. An input signal, Iin in Figure 24, was applied, in the form of a two-amp peak-to-peak sinusoid, which is shown in the Figures. The frequency of the input signal was changed in each simulation.

[0113] In Figure 25, the input frequency was 50 Hz. The left axis applies to the input signal Iin. The right axis applies to the voltage across the capacitor, Vc, which is indicated in Figure 25. It is clear that, at 50 Hz, the output Vc is a sinusoid of about 200 volts, peak-to-peak.

[0114] In Figure 26, the input frequency was 750 Hz. It is clear that, at 750 Hz in Figure 26, output Vc is a sinusoid of about 3,200 volts, peak-to-peak.

[0115] The resonance frequency of Figure 24 is about 2517 Hz, computed using the expression for omega-sub-zero given in Figure 23. In Figure 27, the input frequency was 2517 Hz. It is clear that, at 2517 Hz, Vc is a sinusoid of about 32,000 volts, peak-to-peak.

[0116] In Figure 28, the input frequency was 50 kHz, that is, 50,000 Hz. It is clear that, at 50 kHz, Vc is a sinusoid of about 200 volts, peak-to-peak.

[0117] Figures 25 - 28 are consistent with the postulate that a series RLC circuit can amplify a steady-state sinusoid. At the resonant frequency, Vc is high, 32,000 volts at resonance, and at other frequencies, Vc is lower. It is emphasized that Figures 25 - 28 do not represent voltages produced by coil 310 in Figure 19, but capacitor C in Figure 24, under the assumed conditions.

[0118] The Inventors investigated whether an RLC circuit of the type shown in Figure 24 can produce a similar amplification when the input signal is not a steady-state sinusoid, but a train of pulses of the type used to power the igniters discussed herein. Experimental results indicate an affirmative answer, and the computer simulations to be discussed provide plausibility arguments.

[0119] In Figure 29, coil 370 represents the power cable 315. The power cable is actually a single-turn device, but coil 370 in Figure 24 is represented as a multi-turn device, in order to emphasize the usage of the power cable as the primary of a transformer 373.

[0120] Coil 375 represents the pick-up coil 310 of Figure 19, but coils resembling coil 320 in Figure 20 could be used. In Figure 29, capacitor C and resistor R are elements added to the sensing coil 375, in the pursuit of amplification. It is emphasized that the elements of the circuit of Figure 29 are chosen to withstand operating temperatures consistent with the environment in which they will be used, particularly temperatures, and also vibration.

[0121] The Inventors have found that, for a given pulse train, an artificial resonance frequency can be first computed. Then, in one approach, the artificial resonance frequency is treated as an ordinary sinusoidal steady-state resonance frequency, corresponding to omega-sub-zero in Figure 23. Using the artificial resonance frequency, values of inductor L and capacitor C are chosen in the usual manner, but recognizing that (1) an artificial resonance frequency is being used and (2) steady-state sinusoidal resonance will not apply. Instead, the L and C values obtained are used with a pulsed input.

[0122] In practice, the value of inductor L may be fixed by the materials and geometry of used to construct coil 310 in Figure 19, so that the only value under control of the designer would be that of capacitor C.

[0123] Once the values of L and C are chosen, based on the artificial resonance frequency, it is found that amplification of a pulse train applied to transformer 372 in Figure 29 can occur.

[0124] Alternately, the artificial resonance frequency can be determined graphically, and this will be illustrated by a sequence of examples. Figure 30 illustrates simulation output of the circuit of Figure 29, but when excited by the input signal 400 in Figure 30, which is a triangular current pulse, which is applied to coil 370 in Figure 24. The component values used in Figure 25 for the current simulation were the following: R of 500 ohms, L of one Henry, and C of 0.40 microFarads, as indicated in Figure 30.

The horizontal axis indicates time, in units of milliseconds.

As before, the left axis applies to the input signal, and the right axis applies to the output signal, which is the voltage across capacitor C in Figure 24.

[0125] Figure 30 indicates that the output is a decaying sinusoid which first peaks at about positive 250 volts, at point 405, then peaks at about negative 175 volts, at point 410, and so on. This output response is commonly called an underdamped response in an RLC circuit, and is also called ringing.

[0126] Figure 31 illustrates a simulation using the same triangular input, and the same component values as in Figure 30, with the exception that capacitor C is one-tenth its previous value, and is now 0.040 microFarads. It is seen that the response frequency increases, consistent with the reduction of the value of C. Further, the amplitude of Vc has increased: it now peaks at about 2.4 kvolts, at point 415.

[0127] Figure 32 illustrates a simulation using the same triangular input, and the same component values as in Figure 31, with the exception that inductor L has been cut in half, and is now 0.5 Henry. It is seen that the response frequency increases, consistent with the reduction of the value of L. Further, the amplitude of Vc has increased: it now peaks at about 2.8 kvolts, at point 420.

[0128] Figure 33 illustrates a simulation using the same triangular input, and the same component values as in Figure 32, with the exception that inductor L has been cut to 20 percent of its previous value, and is now 0.1 Henry. It is seen that the

response frequency increases, consistent with the reduction of the value of L. Further, the amplitude of Vc has increased: it now peaks at about 3.3 kvolts, at point 425.

[0129] Figure 34 is an expanded view of Figure 33, spanning from zero to 2.0 milliseconds, and illustrates one concept of the artificial resonance frequency. Time T illustrates the period of the response. The response frequency F, in Hz, is of course 1/T. F is the resonance frequency of the circuit, and is defined in Figure 24.

[0130] Figures 30 - 34 illustrate a graphical approach to selecting an artificial resonance frequency. In a sense, one selects values of L and C to attain an output waveform, as in Figure 34, wherein the upper half of the first sine wave resembles the input waveform. For example, upper half 425 somewhat resembles the input wave form. Alternately, a more mathematical approach can be used.

[0131] In Figure 34, the value T/2 can be termed the half-period of the circuit's resonance frequency. T/2 is the duration of one positive-going, or one negative-going, hump of the decaying sine wave. The Inventors point out that, in the sequence of Figures 30 - 34, as T/2 of Figure 34 approaches the duration TT in Figure 34 of the triangular input pulse, voltage amplification increases. That is, as T/2 approaches duration TT, by changing the values of L and C in Figure 24, capacitor voltage Vc increases.

[0132] This illustrates one approach to setting the artificial resonance frequency. Inductor L and capacitor C are

selected so that they produce a resonance frequency having a half-period T/2 equal to the duration TT of the input pulse. But the input is pulsed, or in the case of the simulations of Figures 30 - 34, triangular.

[0133] This computation can also be used if the input pulse is a rectangular pulse, and not the triangular pulse shown. The duration of the input pulse, such as D in plot 331 in Figure 21, is taken as corresponding to duration TT in Figure 34. Duration D then corresponds to a frequency of 1/D, in Hz. That frequency is taken as the artificial resonance frequency, and the needed L and C are computed, using the equations given in Figure 23, with suitable conversion to radian measure.

[0134] In another approach, the artificial resonance frequency is chosen based on the rise time, or fall time, of the input pulse. In Figure 34, rise time is about one microsecond, and is the time to rise from point 430 to point 435. The artificial resonance frequency is chosen so that T/4, that is, one-fourth of a period T, equals the rise time. Values for L and C are chosen accordingly.

[0135] A similar principle applies to the fall time.

[0136] The input pulse may be a rectangular pulse. Of course, the pulse will not be perfectly rectangular: the leading and trailing edges will necessarily have finite rise and fall times. The artificial resonance frequency is chosen so that T/4, namely, the quarter-period time, equals the rise time, analogous to the triangular case.

[0137] It is pointed out that the artificial resonance frequency is largely determined by the period D in Figure 1. However, period D is not a frequency of the pulse train. Rather, the frequency equals 1/T. Thus, the artificial resonance frequency, and thus the values of L and C computed from that frequency, do not depend completely on the input frequency, but also on the duty cycle of the pulse train.

[0138] The preceding approaches discussed selecting an artificial resonance frequency, based on timing of input pulses. In yet another form of the invention, the artificial resonance frequency is determined by trial-and-error. Simulations are run, as by experimenting with the actual circuit shown in Figure 24, or by using computer software such as SPICE, which simulate that circuit. Various values of L and C are selected, and those providing the desired amplification are then used.

[0139] However, the sizes of L and C can be limited by practical considerations. For example, in a given situation, attainment of resonance may require a capacitor which is extremely large in physical size. Thus, in some situations, components can be chosen to provide operation at a non-resonant condition, but still provide adequate amplification.

[0140] It is pointed out that the computer simulation approach can be very simple, given that many SPICE programs allow parameters to be swept. That is, in sweeping, a range of values for a parameter, such as L, is selected, and the number of values to be used in the range is specified. In sweeping, literally

thousands or millions of different values of L, and also C, can be selected and tested, all using a computer program, with little or no human effort.

[0141] A human then examines the results and chooses those desired.

[0142] At the artificial frequency, values of L and C are computed which provide specific impedances. Those impedances are the phasor impedances computed as if the excitation were steady-state sinusoidal. That is, at the artificial resonant frequency, the sum of the impedances of L and C are set to zero.

That is, $jwL + 1/jwC = 0$, wherein

L is the inductance,

C is the capacitance,

w is the pseudo-resonant frequency, and

j is the imaginary operator.

Once w is chosen, L and C are selected to satisfy the equation given in the preceding sentence.

[0143] Thus, the desired values of L and C are computed as though the system were operating in a steady-state sinusoidal mode, but then L and C are used in a pulsed input mode.

[0144] In addition, the value of R can be important. In one form of the invention, the RLC circuit of Figure 24 is designed to exhibit an underdamped response, in the engineering sense, so that excitation by a pulse will induce the sinusoidal response called ringing. The envelope of the sinusoid decays exponentially. The value of R determines the speed of decay. In one form of the

invention, R is chosen so that the following events occur.

[0145] First, a current pulse generates a spark. That pulse excites the RLC circuit, such as that shown in Figure 29. The RLC circuit goes into ringing, as indicated in Figures 31 - 34. But the R is selected so that the ringing sinusoid decays sufficiently before the next pulse, so that the next ringing sinusoid can be distinguished from the current one.

[0146] In one embodiment, the ringing sinusoid in Figure 35 decreases to 50 percent of its original amplitude A within 1/2 T. Also contemplated is a decrease to 50 percent within any selected time between 0.05 and 0.9 T.

[0147] U.S. Patent 5,523,691, June 4, 1996, Application Number 458,091, issued to Frus, illustrates one approach to detecting spark in an igniter in an aircraft engine. Frus states that inductor L1 in his Figure 1A is first charged by a current. When a normal spark occurs, the inductor L1 rapidly discharges through the IGNITER PLUG.

[0148] However, if the IGNITER PLUG does not produce a spark, then the inductor L1 sees the IGNITER PLUG as a very high resistance. In this case, inductor L1 discharges through a resistor contained within voltage divider 27. This latter discharge requires a significantly longer time. Frus detects the length of the discharge, and when the longer discharge is detected, he infers the absence of spark.

[0149] Frus also states that spark can fail to occur if the voltage produced by exciter 13 falls short of the intended value.

Frus discusses an approach to detecting this failure.

[0150] The Inventors point out that the inductor L1 in Frus does not serve a similar purpose to the coil 310 in Figure 19 herein. For example, Frus' inductor L1 carries current which is delivered to the IGNITER PLUG. In contrast, coil 310 does not do that.

[0151] Another difference is that Frus' inductor L1 must be designed to withstand voltages which certainly exceed 1,000 volts, and probably exceed 20,000 volts. Thus, significant insulation is required between the input and output leads extending from the physical inductor L1, as well as around the coiled wire within the device. In contrast, coil 310 of Figure 19 must withstand a few volts. In one embodiment, coil 310 is designed as an inductor with an operating voltage on its two leads of no more than 5, 10, or 100 volts, in three different embodiments.

[0152] In addition, the inductor L1 of Frus does not seem to be present in an environment where the temperature exceeds 400 F.

[0153] In one form of the invention, a specific starting sequence is used when the gas turbine engine is started, as in the aircraft shown in Figure 18. The pilot causes a starting system to rotate the rotor (not shown) of the engine, or orders a control system (not shown) to initiate a start-up routine. A fuel control (not shown) delivers fuel to the combustor. The igniters in the combustors are actuated.

[0154] If light-off of the engine is not detected, the

pilot then examines an indicator 500 in Figure 18. Indicator 500 is located at the pilot's station in the aircraft, often called the cockpit. That indicator receives a signal from a detector 505, which responds to the voltage signal produced by capacitor C in Figure 19, which will be termed a spark signal. If the spark signal indicates that the igniter is producing sparks, then the indicator 500 indicates the presence of spark, as by producing a light. If the spark signal is absent, then the indicator 500 indicates the absence of spark, as by producing no light.

[0155] From another perspective, the indicator 500 operates oppositely to an analogous indicator in an automobile. The oil-pressure indicator light in an automobile, for example, illuminates when a problem occurs. In contrast, the indicator 500 illuminates when a problem is absent, namely, when the igniter is producing spark.

[0156] A switch 510 can be provided, to allow the pilot to turn off the indicator 500 when knowledge of spark is not desired. Alternately, a control system, not shown, can control when the indicator 500 displays its information.

[0157] Figure 36 illustrates two forms of the invention. The igniter 550 has a proximal end 555 and a distal end 560. The proximal end has a housing 565, which, in this instance, is of cylindrical shape, or circular shape in cross-section. Other cross-sectional shapes are possible.

[0158] A detachable housing 570 is shown, which contains coil L, capacitor C, and resistor R, analogous to the corresponding

elements in Figure 29, and indicated by block RLC. Connectors, wiring leads, coaxial cable 575 or the like allow external detection of a voltage across capacitor C, or other selected component.

[0159] Housing 570 contains an aperture 580 of a cross-sectional shape which matches that of the housing 565. Matching shape means that the two shapes are the same shape, and the same size, so that the aperture 580 fits snugly about the housing 565.

[0160] In one form of the invention, the inductor L is wrapped about the axis of the igniter, as in Figure 19. In another form of the invention, a high-permeability ring surrounds the igniter, and captures the magnetic field B produced by current entering the igniter. The inductor L is wrapped around the ring, as in Figure 20.

[0161] In another form of the invention, the spark detector RLC is made integral with the igniter, as shown in igniter 600 in Figure 36.

[0162] Several additional aspects of the invention are the following. In one form of the invention, an adapter 311 in Figure 19A is provided which mounts to the engine or combustor (neither shown). The igniter threads into the adapter. The adapter contains integral coils 310 which perform the detection function described above.

[0163] It is not necessary that the RLC circuit operate at resonance. Rather, the RLC circuit can be viewed as performing two functions. One is that it amplifies the pulse generated in the

inductor, L. A second is that the RLC circuit produces ringing, or a decaying sinusoid. The ringing causes the detected signal to persist over a longer time than the pulse inducing the ringing, thereby making the pulse easier to detect.

[0164] The triangular wave shown for example in Figure 34 is diagrammatic. The actual signal used in the igniter need not be triangular, but will depend on the requirements of the particular igniter used. Also, the physical properties of the igniter change as it ages, and those properties affect the shape of the pulse applied to it. By analogy, it is well known that, in a capacitor, the current is not in phase with an applied AC voltage. The internal resistance of the capacitor may change with age. That change will cause a change in the phase angle between the current and the voltage, thus illustrating the point that a change in a physical object to which a voltage is applied can change the resulting current in the object.

[0165] The discussion herein was framed in terms of discrete, lumped circuit elements, such as the R, L and C in Figure 24. However, it is observed that similar results can be obtained with distributed elements.

[0166] The application to gas turbine engines in aircraft discussed above is exemplary. In general, the invention is applicable to gas turbines generally, which are used in aircraft, land vehicles, ships, power generation, and other applications. Further, the invention is applicable to spark detection in igniters generally.

[0167] A bleed resistor can be added to bleed charge from capacitor C in Figure 24, and the corresponding capacitor in the RLC circuit. The bleed resistor sharpens the decay of the ringing, thus causing the ringing to die out faster.

[0168] In general, the values of R, L, and C are chosen to provide a detectable signal, such as on capacitor C. One definition of detectable signal can be obtained with reference to K-type thermocouples, which are used extensively in gas turbine engines. Such thermocouples produce signals in the range of 250 millivolts. Thus, one definition of a detectable signal can be a signal exceeding 250 millivolts. Consistent with that definition, in one experiment, the inventors obtained a signal of 470 millivolts across the capacitor C.

[0169] One feature of the invention is that it allows the capacitor in the RLC circuit to be positioned remotely from the other components, and thus in a cooler location than the location of the coil 310 in Figure 19. In one embodiment, the capacitor C can be positioned in a room-temperature environment, or cooler, where room temperature is taken as nominally 75 degrees F.

[0170] This can be significant because many capacitors have a practical temperature limit of 175 degrees F. But the location of coil 310 in Figure 19 will probably exceed 400 degrees F.

[0171] The discussion above referred to delivering a signal indicating proper spark is occurring to a pilot station. This signal could also be delivered to maintenance personnel, either in the apparatus which utilizes the gas turbine engine, or to remote

maintenance personnel. The signal can also be delivered to more than one pilot station.

[0172] Numerous substitutions and modifications can be undertaken without departing from the true spirit and scope of the invention. For example, the discussion above was framed in terms of aircraft gas turbine engines. However, the invention can be used in other types of gas turbines, such as land-based gas turbine engines used in power generation and pumping, or in ships. In addition, the invention is not restricted to gas turbine engines, but can be used in igniters generally, which are used in various combustion applications.

[0173] Also, it is not required that the invention be operated in a hot environment, but the invention does provide the ability to withstand high-temperatures, as explained above.

[0174] What is desired to be secured by Letters Patent is the invention as defined in the following claims.